Rubidium-rich Asymptotic Giant Branch stars in the Magellanic Clouds

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Abstract.   The Magellanic Clouds (MCs) offer a unique opportunity to study the stellar evolution and nucleosynthesis of massive Asymptotic Giant Branch (AGB) stars in low metallicity environments where distances are known. Rubidium is a key element to distinguish between high mass AGB stars and low mass AGBs or other type of astronomical objects such as massive red supergiant stars. Theoretically, high mass AGBs are predicted to produce a lot of Rb. We present the discovery of massive Rb-rich AGB stars in the MCs, confirming for the first time that these stars also exist in other galaxies. Our findings show that these stars are generally brighter than the standard adopted luminosity limit ($M_{bol} \sim -7.1$) for AGB stars. The observations of massive MC AGBs are qualitatively predicted by the present theoretical models. However, these theoretical models are far from matching the extremely high Rb overabundances observed. This might be related with an incomplete present understanding of the atmospheres of these stars.

1.   Introduction

The Magellanic Clouds (hereafter MCs) provide a unique opportunity to study the evolution and nucleosynthesis of low- and intermediate-mass stars ($0.8 < M < 8 \, M_\odot$) in low metallicity environments where distances - and hence luminosity - are known. Low- and intermediate-mass stars experience thermal pulses and strong mass loss on the Asymptotic Giant Branch (AGB; e.g., Herwig 2005). Repeated thermal pulses and "3rd dredge-up" events can convert the originally O-rich AGB star into a C-rich one. However, in the case of the more massive AGB stars ($M > 4 \, M_\odot$), Hot Bottom Burning (HBB; e.g., Mazzitelli et al. 1999) prevents the C-star formation and these stars remain O-rich despite the dredge-up. The activation of HBB in massive AGB stars is supported by previous studies on visually bright MC AGB stars (e.g., Plez et al. 1993) and on heavily obscured O-rich AGBs - the so-called "OH/IR" stars - of our Galaxy (García-Hernández et al. 2006, 2007).

AGB stars also produce heavy neutron-rich elements (*s*-process elements) such as Rb, Zr, Sr, Nd, Ba, etc., which can be dredged-up to the stellar surface (e.g., Busso et al. 1999). In the more massive AGB stars, free neutrons are predicted to be mainly released by the $^{22}Ne(\alpha,n)^{25}Mg$ reaction, while the $^{13}C(\alpha,n)^{16}O$ reaction seems to be the dominant neutron source in lower mass AGB stars. Rb is a key element to distinguish between the operation of the ^{13}C versus the ^{22}Ne neutron source in AGB stars and,

as such, is a good indicator of the progenitor stellar mass[1]. This is because the relative abundance of Rb to other *s*-process elements such as Zr (i.e., the Rb/Zr ratio) is sensitive to the neutron density owing to branchings in the s-process path at ^{85}Kr and ^{86}Rb (e.g., van Raai et al. 2008b). Interestingly, we discovered strong Rb overabundances (up to 10−100 times solar) with apparently only mild Zr enhancements in massive galactic O-rich AGB stars (García-Hernández et al. 2006). This work provided the first observational evidence that ^{22}Ne is the dominant neutron source in the more massive AGB stars. Surprisingly, Rb was not found to be overabundant in the few unobscured O-rich massive AGBs previously studied in the SMC (Plez et al. 1993). Here, we present the first detections of massive Rb-rich AGB stars in the MCs.

2.   Optical spectra and abundances

High-resolution (R~60,000) optical UVES spectra were obtained for a carefully selected sample of heavily obscured O-rich AGBs in the MCs (see García-Hernández et al. 2009, for more details). These stars are suspected to be the most massive and extreme AGBs known in the Clouds. Sample spectra around the 7800 Å Rb I line are shown in Fig. 1. We found four Rb-detected AGB stars in the LMC and one in the SMC (see Fig. 1).

The abundances (or upper limits) of the elements Rb and Zr (when possible) were derived from the 7800 Å Rb I line and the ZrO molecular bands, respectively, and by following the procedure that we used for the galactic O-rich AGB stars (García-Hernández et al. 2006, 2007) (see also García-Hernández et al. 2009, for more details). The spectroscopic effective temperatures and abundances are summarised in Table 1. The uncertainties of the derived abundances are estimated to be 0.8 and 0.5 dex for Rb and Zr abundances, respectively.

Table 1.   Spectroscopic temperatures and abundances for the Rb-rich MC AGBs

IRAS name	T_{eff}	[Rb/z]	[Zr/z]	Type
04498−6842	3400	+5.0	≤ +0.3	OH/IR
04407−7000	3000	+3.2	. . .	OH/IR
04516−6902	3000	+3.2*	≤ +0.3	OH/IR?
05558−7000	3400	+2.8	. . .	OH/IR
00483−7347	3400	+1.7*	. . .	OH/IR?

3.   Luminous Rb-rich MC AGBs

The main result of our spectroscopic survey is that we have detected strong Rb I lines in AGB stars (four stars in the LMC and one in the SMC) in a low-metallicity extragalactic system. These first detections of extragalactic Rb-rich AGB stars confirm that these stars also exist in other galaxies. Similarly to our Galaxy, the Rb-detected stars in the

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[1]Note that other astronomical sources such as massive red supergiant stars are not expected to overproduce Rb.
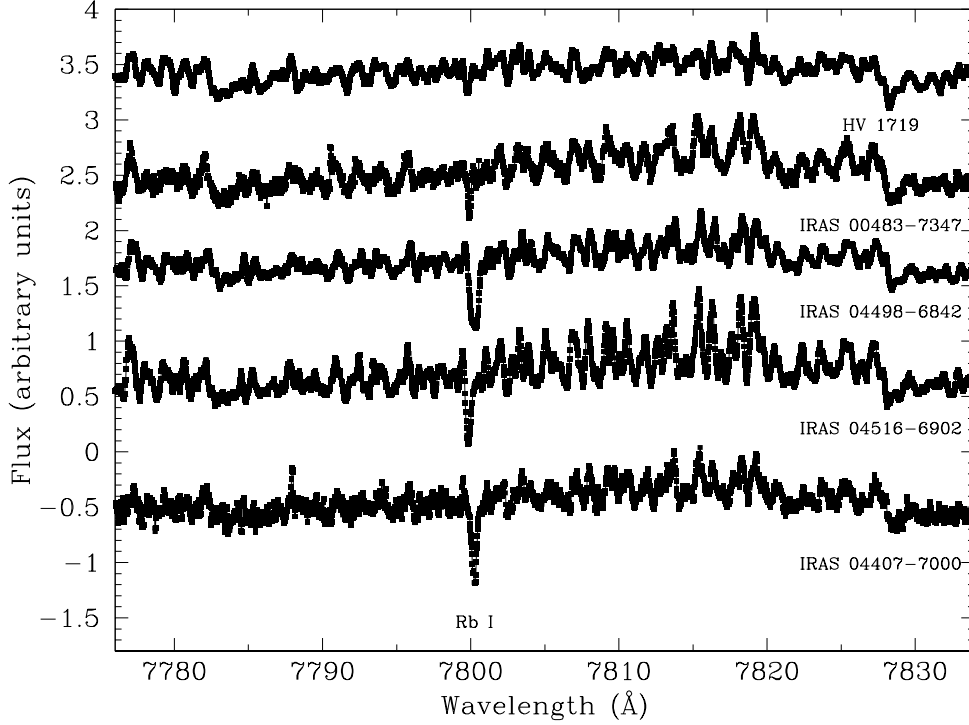
Figure 1.   Sample spectra around the 7800 Å Rb I line. The lower three stars (IRAS 00498-6842, 04516-6902, and 04407-7000) are Rb-rich LMC stars. The upper two stars are from the SMC. IRAS 00483-7347 is the heavily obscured Rb-rich AGB discovered in the SMC, while HV 1719 is a visually bright HBB SMC AGB with a much weaker Rb I line.

MCs belong to the type of so-called OH/IR stars (Table 1). Unfortunately, we could estimate photospheric Rb abundances in only three LMC Rb-rich stars due to the clear presence of blue-shifted circumstellar Rb I lines in the other Rb-detected stars (those stars marked with an asterisk in Table 1). The extremely high Rb abundances observed (up to $10^3 - 10^5$ times solar) among the LMC stars are even greater than those displayed by their Galactic counterparts (García-Hernández et al. 2006).

A common characteristic of the Rb-rich stars that sets them apart from other AGB stars is their bolometric luminosity. A plot of M_{bol} vs. [Rb/z] is shown in Fig. 2. The Rb-rich stars in the LMC are brighter ($-8 < M_{bol} < -7$) than the AGB stars with no Rb detected. The jump of the Rb abundances at luminosities of M_{bol} of -7.1 is intriguing (Fig. 2). This bolometric luminosity is the generally adopted limit for AGB stars (Paczyński 1971). Massive red supergiants have been thought to be more luminous than the standard limit of $M_{bol} \sim -7.1$. Thus, our observations confirm that massive Rb-rich AGB stars are generally brighter than this limit due to a luminosity contribution from HBB. HBB models suggest that the Rb-rich LMC AGB stars with $M_{bol} < -7$ are the descendants of stars with initial masses of at least $\sim 6-7$ $M_\odot$ (see Fig. 7 in Ventura et al. 2000).
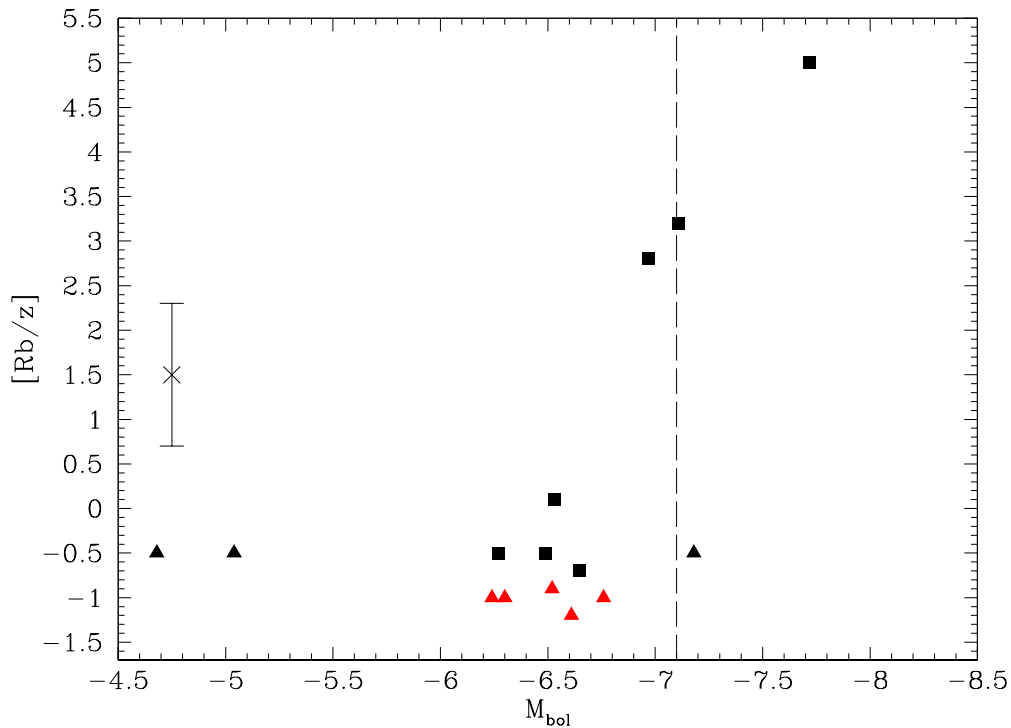
Figure 2.   Observed Rb abundances (squares and triangles for the LMC and SMC, respectively) versus M_{bol}. The Li-rich HBB-AGBs previously studied in the SMC (Plez et al. 1993) are also included. A typical error bar of ±0.8 dex is shown. The dashed vertical line marks the theoretical luminosity limit (M_{bol}=−7.1; Paczyński 1971) for AGB stars.

4.   Models vs. observations: a Rubidium problem

We found a Rb problem that is mainly posed by the the four Rb-rich LMC AGB stars. This Rb problem has two parts: the extremely high Rb abundance and the extraordinary [Rb/Zr] ratio. Our detections of Rb-rich LMC AGB stars is assured by inspection of our spectra (Fig. 1). However, the strong Rb overabundance ([Rb/z]∼ +2.8 to +5.0) may be somewhat uncertain because the Rb ɪ line is strong and saturated with possible circumstellar contamination. In addition, our upper limit to the Zr abundance that gives the extraordinary [Rb/Zr] ratio of 3 to 4 (Table 1) comes from a fit to ZrO bands.

The Rb overabundance is very likely the consequence of the *s*-process nucleosynthesis via the high neutron density ^{22}Ne neutron source, which is expected to be efficiently activated in massive AGB stars. Although the increase in the Rb abundance between the low and high neutron density *s*-process paths (i.e., ^{13}C vs. ^{22}Ne) is about an order of magnitude, the predicted Rb/Zr ratios, however, do not reach extreme values. Present theoretical predictions for massive AGB models at the LMC and SMC metallicities computed for the ^{22}Ne neutron source are far from matching the extremely high Rb enhancements and the extraordinary [Rb/Zr] ratios (Table 1) that we observe (García-Hernández et al. 2009). Thus, within the framework of the s-process it is not

possible to produce extremely high Rb abundances without co-producing Zr at similar levels. However, these massive AGB nucleosynthesis models can qualitatively describe the observations of Rb-rich AGBs in the sense that increasing Rb overabundances with increasing stellar mass and with decreasing metallicity are theoretically predicted (van Raai et al. 2008a,b).

The extremely high Rb enhancements and the extraordinary [Rb/Zr] values could suggest that a nucleosynthesis process not predictable yet is at work in these massive Rb-rich AGB stars. However, a failure of the adopted models to represent the real stars may explain the large discrepancy between models and observations. In addition, the use of the ZrO bands to estimate the Zr abundance as well as non-LTE effects may be contributing factors too. More realistic models (e.g., the inclusion of a circumstellar envelope or the application of dynamical models) would help to solve the discrepancy observed. Despite the uncertainties in the Rb abundance determinations, the fact that Rb-rich AGB stars are found among the most luminous AGB stars (i.e., confined to bolometric magnitudes $M_{bol} = -7.1$ and brighter; Fig. 2) is assured. This result will help to identify these stars in other galaxies of the Local Group.

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